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(54) **A Process and Installation for Utilising Heat Generated by a Nuclear Reactor**

(57) An installation for utilising heat generated by a high temperature nuclear reactor comprises two closed circuits, a primary circuit for circulating helium comprising a high temperature reactor (1), a blower (3) for circulating the helium and a gas-to-gas heat exchanger (6), the primary circuit being housed in a concrete pressure vessel. The secondary circuit, in which a gas mixture, e.g. helium and nitrogen is circulated, absorbs heat from the primary circuit at the heat exchanger (6). The secondary circuit which is outside the pressure vessel comprises a turbine (8), three coolers (13, 15 and 17) and three compressor stages (14, 16 and 18) between a low pressure side and a high pressure side of a heat transfer recuperator (12).

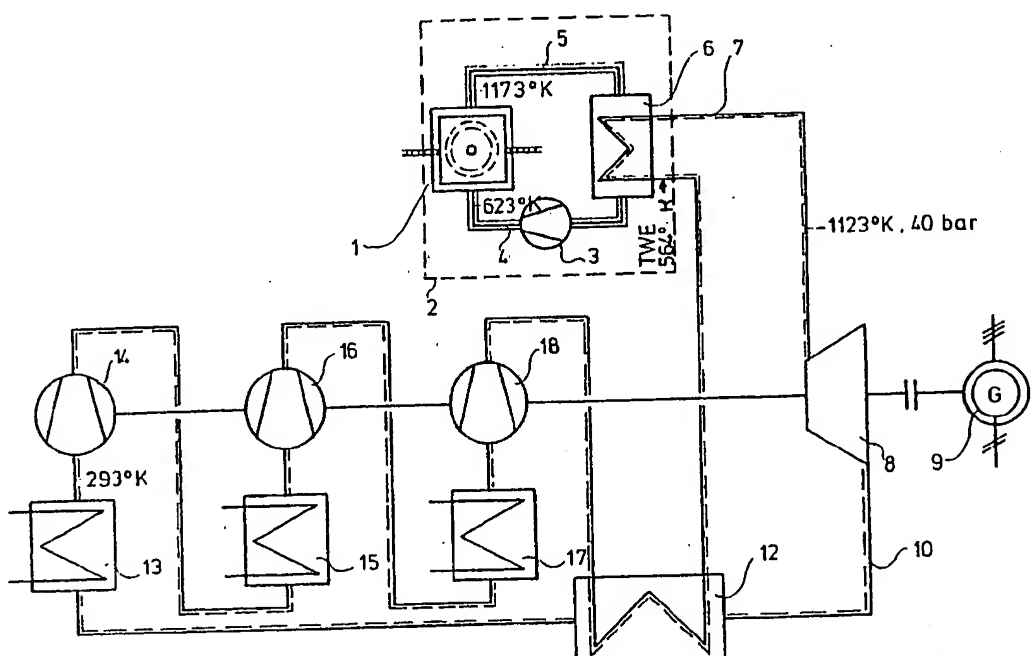

Fig. 1

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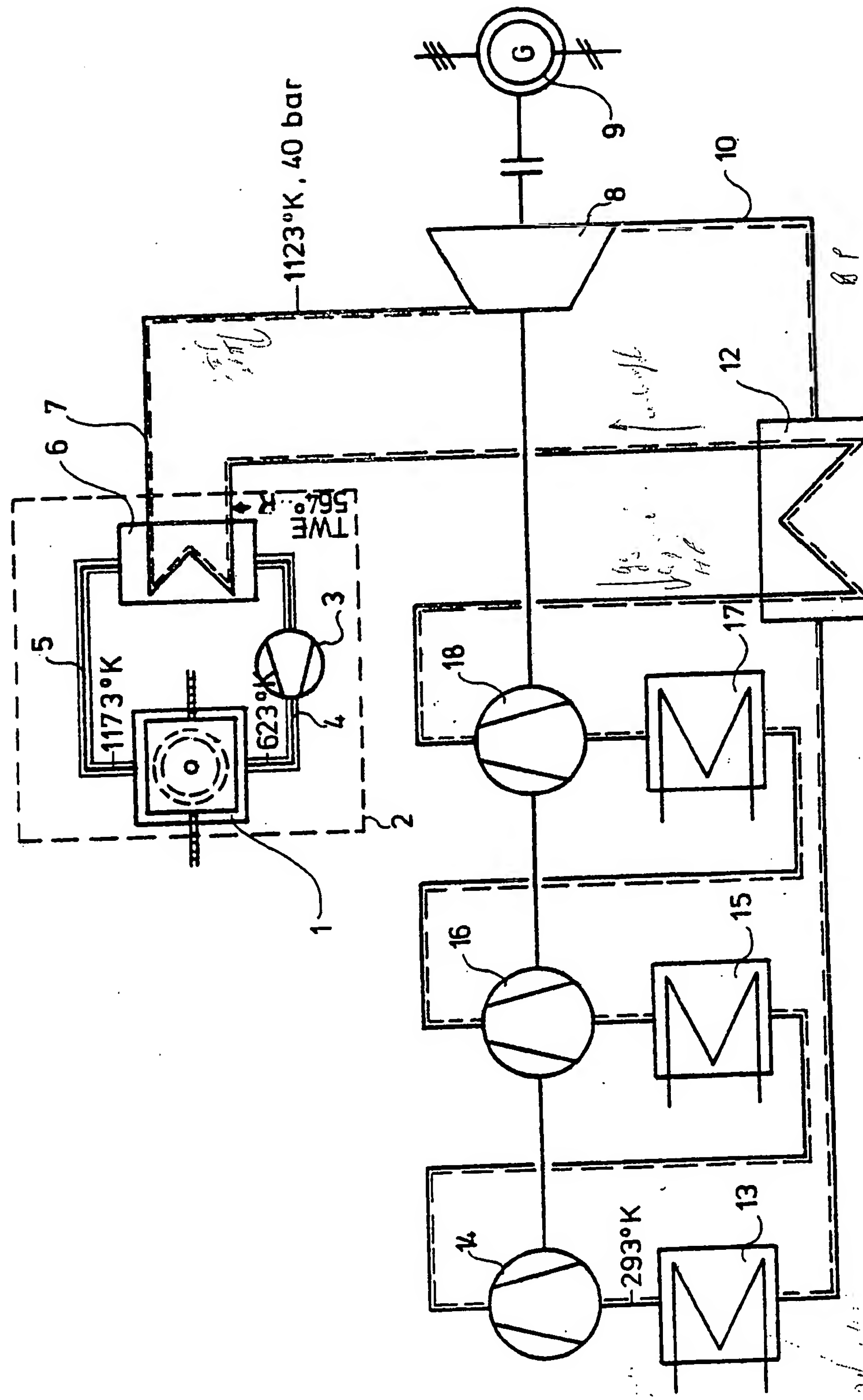
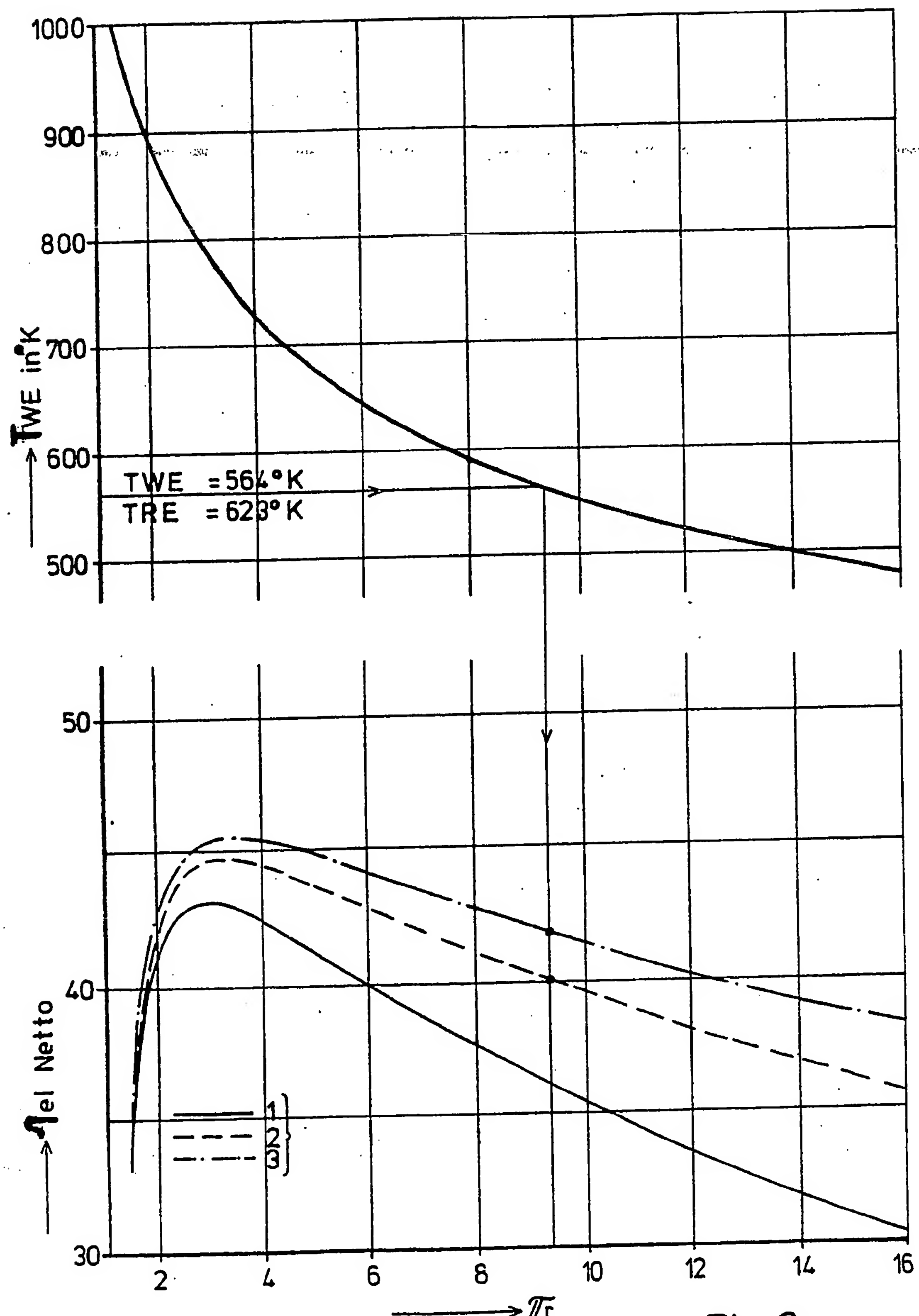


Fig. 1


1000
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TWE in °K
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Fig. 2

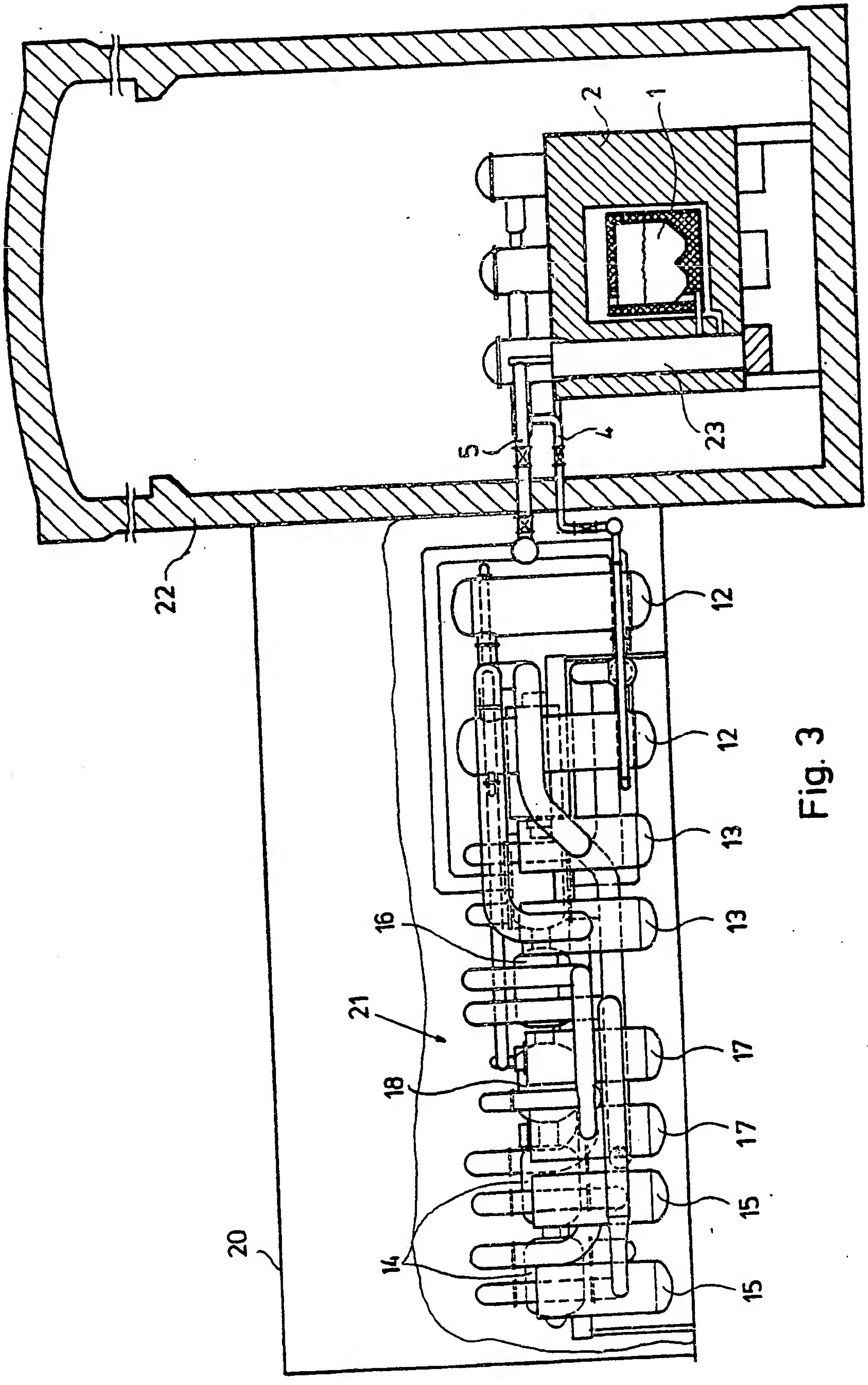

Fig. 3

SPECIFICATION

A Process and Installation for Utilising Heat Generated by a Nuclear Reactor

The present invention relates to a process and installation for utilising heat generated by a high temperature nuclear reactor. More particularly, the invention concerns a process for the utilisation of heat, generated by high temperature nuclear reactors, using a gas turbine operated in a closed circuit with a gas, which does not change its state and to which the reactor heat is fed in a compressed state. The gas partially delivers up its latent energy under expansion in the turbine, subsequently flows through at least one recuperator on the low pressure side thereof, is then compressed, passes through the recuperator on the high pressure side and after completion of the circuit is re-cycled again.

It is known to utilise the heat, which is generated by nuclear reactors, in a gas turbine operated in a closed circuit. Although the performance of this process has proved in itself to be basically correct some difficulties arise when utilising the heat of high temperature reactors. The concept of using a high temperature reactor on the one side and a gas turbine operated in a closed circuit on the other side therefore requires further consideration in order to arrive at a better starting point of the known process.

High temperature reactors (HTR), apart from the possibility of delivering process heat at a high temperature level, offer some significant advantages in the generation of electrical energy with the aid of a closed gas turbine circuit, including the following:

The high reactor exit temperature leads to good process efficiencies and a reduction of the waste heat. The environmental loading by waste heat is substantially lower than perhaps in the case of light water reactors. The base HTR concept disposes of some advantages in terms of safety and technology, namely the great thermal capacity of the reactor core, high temperature strength and high holding-back capability of the combustion elements, strongly negative temperature co-efficient of the reactivity and if a breakage or fault occurs the pressure can be relieved, without a complete loss of the coolant. Accordingly, the requirements on the starting speed of the after-heat removal systems are only small by comparison with other reactor structure concepts.

The core fuel supplies can be stretched by the HTR-reactors through conversion of thorium into splittable uranium 233 and the supply security can be increased. Furthermore, the HTR possesses a particularly favourable neutron economy and thereby attains an efficient fuel utilisation. The required supply of natural uranium of the HTR in the open fuel circuit is about 1/3, and in the closed fuel circuit nearly 2/3 lower than with the corresponding pressure water reactor (c.f. G. Kolb; study on the economics of the current generation by high temperature reactors; KFA Jülich, printed specification Jül-1527, August 1978). A further lowering of the natural uranium over a long term is possible by highly-converting HTR-systems.

The connection of a closed gas turbine circuit downstream of the HTR by the use of the sensing regulation (pressure level regulation) makes possible particularly favourable partial load efficiencies which hardly deviate from the full load efficiency.

The closed gas turbine in conjunction with the HTR possesses a particularly great potential for further development. Increases in the reactor exit temperature and thereby the gas turbine entry temperature can further improve the installation efficiency. By increasing the pressure level in the gas turbine circuit, the performance of the installation can be increased or it can be built more compactly.

The heat to be removed in a preliminary cooler and an intermediate cooler arises at a relatively high temperature level. Thus, one obtains a greater temperature spread between the circuit gas and the coolant. A smaller cooler and an easing of the problems caused by their erection is made possible through the economical use of dry cooling towers.

In a power-heated coupling, the major part of the waste heat can be utilized for district heating without influencing the generation of electrical energy.

In spite of these recognised advantages of the HTR with a closed gas turbine circuit connected downstream of the HTR, this type of installation could hitherto not be introduced. The most important reasons for the previous rejection can be defined as follows:

The high costs of the integrated manner of construction and thereby the unsatisfactory economics compared with competing concepts by

(a) the large size and thereby particularly cost-intensive concrete pressure vessel,

(b) the high demands in terms of safety technology on the components in the contaminated circuit, and

(c) the constraints in the structuring of the appliances and pipe ducts hitherto did not permit to exhaust all means for increasing the efficiency.

The problems in the assembly, inspection, maintenance and repairability due to geometric and radiological accessibility.

The task was therefore set of modifying the concept of a closed gas turbine circuit with a nuclearly operated HTR in the sense that it is in respect of the costs of the entire reactor installation at least in agreement with the THTR (*t*horium *h*igh *t*emperature *r*eactor with primary helium and secondary steam circuit), that high demands in terms of safety technique are fulfilled and that the components more strongly requiring maintenence, i.e. the parts of the gas turbine circuit, remain

accessible, in particular they do not have to be built into the wall of the concrete pressure vessel which surrounds the actual reactor.

According to one aspect of the present invention there is provided a process for the utilisation of heat generated by a high temperature nuclear reactor comprising the steps of circulating gas through a closed primary circuit to a high temperature nuclear reactor at an entry temperature of between 520° and 680°K, heating the gas in the reactor to an exit temperature of between 1020 and 1220°K, passing the heated gas of the primary circuit through a heat exchanger to transfer heat from the heated gas to compressed gas in a closed secondary circuit, extracting energy from the heated compressed gas under expansion thereof to drive a gas turbine having a pressure ratio between 4 and 12, extracting heat from the expanded gas, thereafter cooling the expanded gas in at least two stages, compressing the cooled gas, transferring said extracted heat to the compressed gas, and returning the compressed gas to the heat exchanger for recirculation.

In the use of this process, all components of the gas turbine circuit with the exception of the primary-secondary side heat exchanger can be erected freely using a conventional method of construction. Only the few components of the primary circuit are enclosed by the concrete pressure vessel.

A comparison of the HHT-single-circuit and HHT-gas-to-gas two-circuit concept with gas turbine connected downstream in a closed circuit shows that in the two-circuit installation, apart from the components also present in the single-circuit installation, additional circulating blowers must be provided in the primary circuit and heat exchanger. For power ratings and efficiency considerations, it is necessary that the driving load of the blowers must be increased compared with the single-circuit installation. The build-up at the primary side, inclusive of the heat exchanger, is identical with that of the nuclear process heat installations. Heat exchangers already developed in the so-called PNP-project (*p*rototype installation of *n*uclear *p*rocess heat) can therefore also be used in the HHT-two-circuit installation.

Compared with the single-circuit installation, the two-circuit installation has the following advantages:

The same primary circuit structure as in the PNP-project and the low reactor entry temperature possible through particular design of the gas turbine circuit make possible a common reactor concept with already developed or being developed components of the PNP-project. In that case, the low reactor entry temperature is particularly advantageous for the liner insulation, the cut-off rods and the thermal shield. The two-circuit installation permits an exhaustion of the high temperature potential of HTR. The most expensive individual component of the entire installation, the pressure vessel, becomes appreciably smaller and thereby more economical, since the vessel need receive fewer components.

Other factors to be taken into consideration are the cost reduction for the reactor protective building and in personnel costs for monitoring and maintenance operations. The high requirements of the acceptance procedure with strict safety requirements remain restricted to a few primary circuit components. Furthermore, the two-circuit installation reduces likely faults which may arise as follows:

(a) the fault of blade damage on a compressor or on a turbine with the rapid pressure equalisation processes connected therewith does not, as in the single-circuit installation, lead to overloadings of the insulation and reactor,

(b) an ingress of the lubricant oil present in the slide bearings into the gas turbine circuit cannot harm the reactor or the insulation.

The turbine pressure ratio π_T is chosen according to the composition of the circuit fluid of the secondary circuit and in accordance with the reactor values. In the case of for example pure helium, the value π_T is set low, possibly $\pi_T=4$; for N_2 10 ... 12, the required pressure ratios theoretically lie still higher for CO_2.

The process according to the present application makes possible the free choice of the secondary circuit fluid and thereby an optimisation of costs of the installation components. While the gas of the primary circuit is preferably helium, the gas of the secondary circuit can be a gas mixture. Advantageously, the following composition is chosen:

48 to 52% by volume of helium
48 to 52% of N_2

and a small oxygen content (approximately 0.5% by volume) for prevention of nitration. Since the minimum cost is relatively low, other compositions can also be chosen.

According to another aspect of the present invention there is provided an installation for carrying out the process as set forth above, comprising a pressure vessel, a closed primary circuit arranged in the pressure vessel for circulation of gas through a high temperature nuclear reactor, a heat exchanger arranged in the pressure vessel to extract heat from the gas of the primary circuit, and a closed secondary circuit for circulation of gas to receive the extracted heat, the secondary circuit being disposed externally of the pressure vessel and comprising a turbine driveable by the gas of the secondary circuit at least two cooling devices to cool the gas of the secondary circuit and at least three compressors for compressing the cooled gas, the cooling devices and compressors being arranged downstream of the turbine and upstream of the heat exchanger.

The turbine located externally of the pressure vessel does not operate in the contaminated circuit

and is freely accessible at any time so that assembly, inspection, maintenance and repairability are very much simplified. A shortening of the erection time is also to be expected. A complete new development of the turbo-set particularly towards a compact underground method of construction is not required since the construction and the operational experiences of the hitherto built closed gas turbine installation, cf. construction of the helium turbine Oberhausen, can be called upon.

An embodiment of the present invention will now be described by way of example, with reference to the accompanying drawings, in which:

Figure 1 shows a HHT-two-circuit installation which operates by a process exemplifying the invention,

Figure 2 shows two graphs in which the entry temperature into the primary-secondary side heat exchanger and the electrical net efficiency are illustrated for a He-N_2 mixture as circuit fluid in dependence on the turbine pressure ratio π, and

Figure 3 shows a diagram, partly in section of an installation including a reactor protective building with a reactor pressure vessel and a turbine circuit connected downstream thereof.

Referring now to the drawings in detail, the process for the utilisation of the generated heat of nuclearly operated high temperature reactors is carried out by using an installation comprising a gas turbine operated in a closed circuit with the reactor. In this embodiment the entire circuit is divided into a primary circuit and a secondary circuit.

In the primary circuit, a known high temperature reactor (HTR) 1 is incorporated in a concrete pressure vessel 2 with observation of the usual safety criteria. The HTR 1, may be, for example, a ball heap reactor similar to the THTR in Hamm-Uentrop.

A current of helium is conveyed by a blower 3 through ducts 4 and 5 in closed circuit through a reactor 1 and a primary-secondary sided heat exchanger 6. The compressed gas of the secondary circuit is conducted into and out of the heat exchanger 6 through a duct 7 which leads into and out of the concrete pressure vessel 2.

The heat exchanger 6 is accordingly a gas-to-gas heat exchanger. The selection of gases, which are employed in both the circuits, is important. While it has proved to be inescapable to use helium as a circuit fluid in the case of the primary circuit, expense, the thermal capacity, the thermal conductivity and the density can be considered in the choice of the circuit medium for the secondary circuit.

It has proved to be advantageous to use a mixture of helium (He) and nitrogen (N_2) with a small oxygen component, for which the optimum mixture results from equal volume proportions of He and N_2 as well as 0.5% oxygen (O_2); the oxygen component serves for prevention of the nitration of the metal surfaces. However, these values can readily be departed from within the scope of the initially named limits.

In the embodiment in Figure 1, the entry temperature of the reactor is 620° Kelvin and the exit temperature 1173° Kelvin. According to operational conditions, these temperatures can be increased or decreased as will be hereinafter described. The entry temperature of the gas (secondary side) into the heat exchanger 6 is approximately 60° lower than the entry temperature into the reactor, since the gas temperature is increased by the blower 3.

The output fed in the reactor 1 and blower 3 to the gas of the primary circuit is transferred in the heat exchanger 6 to the compressed circuit fluid of the secondary circuit. In the present embodiment, it has a temperature of approximately 1123° Kelvin and a pressure of 40 bar. The gas of the secondary circuit and the primary circuit does not change its state in the entire circuit; they thus remain constantly in the gaseous state. After passage through the heat exchanger, the compressed gas is circulated to a turbine 8, in which it partially delivers up its latent energy under expansion and thus delivers a useful output to drive a generator 9 and to drive a plurality of circuit compressors.

Subsequently, the gas reaches a temperature of approximately 594°K and a pressure of 4.3 bar and passes through a duct 10 to a recuperator 12, comprising a low pressure side and a high pressure side. The gas flows first through the low pressure side and the utilisable heat energy liberated is transferred to the compressed gas flowing through the high pressure side. The gas flows from the recuperator 12 to a preliminary cooler 13, at the output side of which the gas falls to a temperature of approximately 290°K, to a lower pressure compressor 14, a first intermediate cooler 15, a medium pressure compressor 16, a second intermediate cooler 17 and a high pressure compressor 18. Subsequently, the high pressure side of the recuperator 12 is traversed, completing the circuit. The gas is then recirculated through the heat exchanger 6, in order to receive the process heat, in a compressed state. The compressors 14, 16 and 18 are driven by a main shaft of the turbine 8, in some circumstances with smaller loading by the use of known gears.

During recooling of the gas to the compressor entry temperature in the preliminary cooler 13 and in the intermediate coolers 15 and 17, the quantity of heat to be conducted to the environment is withdrawn in a so-called loop process. After the pressure increase in the low pressure, medium pressure and high pressure compressor, the gas traverses the high pressure side of the recuperator 12 and receives the heat still available after driving the turbine. Only thereafter does the gas return to the heat exchanger 6. Almost the entire gas turbine circuit, with the exception of the heat exchanger 6, can be erected by conventional construction methods freely externally of the concrete pressure vessel 2, only the few components of the primary circuit being enclosed by the concrete pressure vessel 2.

In the illustrated two-circuit installation, an optimisation of costs is possible through the choice of the circuit medium or through the choice of suitable gas mixtures in the secondary circuit. By the use of pure helium, the dimensions of the heat-exchanging appliances are reduced and thereby become more economical, while the dimensions of the turbo-machines and thereby their costs of construction fall by using gases of high molecular weight, possibly of N_2. The minimum cost for a gas turbine circuit without a heater lies in the case of He-N_2 mixtures at a volume proportion of about 50% He and correspondingly a mass proportion of 12.5%. This gas mixture is suitable also for the secondary circuit.

In particular, it is necessary that the reactor entry temperature is approximately 600 to 650°K, with a reduction in the liner insulation, the thermal shield and cut-off rods also become simpler and the load for the primary circuit blower is reduced. The heat load to be transferred in the recuperator and thereby the overall size and building costs thereof also fall with increasing pressure ratio. The graphs shown in Figure 2 illustrate that the pressure ratio must be increassed appreciably beyond the value of the optimum pressure ratio, which is dependent on the kind of fluid used in the circuit and which in this case lies at about $\pi=3$. The reduction of the efficiency effected thereby can be compensated to the greatest part by an increase in the number of the intermediate coolings as is evident from the lower graph in Figure 2. If for example the process is operated with a reactor entry temperature $T_{RE}=623$°K, which corresponds to a secondary side heat exchanger entry temperature $T_{WE}=564$°K, then the turbine pressure ratio π_T must lie at about 9.3. If with this pressure ratio only one intermediate cooling was to be provided, then an electrical efficiency of only 36.2% would result (solid line of the lower graph). An increase in the number of intermediate coolings leads in the case of increased process pressure ratios to appreciable improvements in efficiency; at two intermediate coolings, the efficiency in the same example is 40%, with three intermediate coolings approximately 41.8%.

Example for a Circuit Design

The following data provides a deliverable useful output of 678 MW

Net output (bus bar)	678.0 MW
Internal requirements	12.0 MW
Pump load (entire circuit)	0.3 MW
Primary circuit blower	28.3 MW
Generator terminals (gross)	718.6 MW
Generator losses	13.2 MW
Coupling	731.8 MW
Mechanical losses	4.5 MW
Internal load	736.2 MW
Reactor	1689.2 MW
Primary/secondary side heat exchanger	1717.5 MW
Heat losses	10.0 MW
Transferred to secondary circuit	1707.5 MW
Recuperator	515.3 MW
Turbine	1612.9 MW
Compressor (total)	876.7 MW
Waste heat (total)	971.3 MW
Net efficiency	40.1%
Throughput (in the ND-compressor)	1926.8 kg/s.

A part vertical section through an entire installation is illustrated in Figure 3. The installation comprises a machine housing 20 for a single-shaft turbo-set 21 with eight recuperator units 12, four preliminary coolers 13, four intermediate coolers 15, for recooling the fluid medium between low pressure and medium pressure compressors 16 and 18 and four intermediate coolers 17 for recooling the gas between the medium pressure and high pressure compressors.

A reactor protective building 22 encloses the concrete pressure vessel 2 for the high temperature reactor 1. All components of the primary circuit are accommodated in separate chambers 23. A central chamber and six other chambers 23 are provided for the reception of the primary-secondary side heat exchangers and four further chambers 23 for the reheat removal system. Six hot gas and six cold gas ducts 4 and 5, respectively, connect the heat exchangers with the reactor and the turbo-set arranged in the machine housing 20.

Use of a Ball Heap Reactor of 500 MW in a HHT-gas-to-gas Two-circuit Installation

The heat generation system comprising a ball heap reactor of 500 MW, planned for the different concepts of the coal gasification is usable also for a HHT-gas-to-gas two-circuit installation. To increase a life duration of the heat exchanger, the reactor exit temperature of 950°C (=1223°K) can be lowered to 900°C (1173°K). The loss in efficiency occurring in this case is absorbed by the increase in the number of intermediate coolers to three. Such an installation has for example the following design data:

Loads:

Net (bus bar)	209.7 MW
Internal requirements	3.7 MW
Pump load	0.1 MW
Primary circuit blower	8.4 MW
Generator terminals (gross)	221.9 MW
Generator losses	4.1 MW
Coupling	226.0 MW
Mechanical losses	1.3 MW
Internal load	227.3 MW
Reactor	500.0 MW
Primary/secondary side heat exchanger	508.3 MW
Heat losses	3.0 MW
Transferred to secondary circuit	505.4 MW
Recuperator	176.2 MW
Turbine	477.9 MW
Compressor (total)	250.6 MW
Waste heat (total)	278.1 MW
Net efficiency	41.9%
Throughput (in the ND-compressor)	570.3 kg/s.

A HHT two-circuit installation, with gas as a fluid in both circuits, has the advantage of simplifying the assembly, maintenance, inspection and repairability of the installation. Consequently, the demand for the two-circuit installation is considerably higher than for a single-circuit installation. In addition, the size of the concrete pressure vessel and thereby the space enclosing the reactor protective housing are reduced. Restrictions in the structuring of the installation, especially with regard to the turbo-machine, need no longer to be taken into account.

A further substantial advantage in the installation and process of the invention is that only one reactor development is needed for such different projects as PNP-reactors and HHT-reactors because the essential operating parameters, especially the entry temperature, lie in the same range.

Claims

1. A process for the utilisation of heat generated by a high temperature nuclear reactor comprising the steps of circulating gas through a closed primary circuit to a high temperature nuclear reactor at an entry temperature of between 520° and 680°K, heating the gas in the reactor to an exit temperature of between 1020 and 1220°K, passing the heated gas of the primary circuit through a heat exchanger to transfer heat from the heated gas to compressed gas in a closed secondary circuit, extracting energy from the heated compressed gas under expansion thereof to drive a gas turbine having a pressure ratio between 4 and 12, extracting heat from the expanded gas, thereafter cooling the expanded gas in at least two stages, compressing the cooled gas, transferring said extracted heat to the compressed gas, and returning the compressed gas to the heat exchanger for recirculation.

2. A process as claimed in claim 1 and substantially as hereinbefore described with reference to the accompanying drawings.

3. An installation for carrying out the process as claimed in claim 1, comprising a pressure vessel, a closed primary circuit arranged in the pressure vessel for circulation of gas through a high temperature nuclear reactor, a heat exchanger arranged in the pressure vessel to extract heat from the gas of the primary circuit, and a closed secondary circuit for circulation of gas to receive the extracted heat, the secondary circuit being disposed externally of the pressure vessel and comprising a turbine drivable by the gas of the secondary circuit, at least two cooling devices to cool the gas of the secondary circuit and at least three compressors for compressing the cooled gas, the cooling devices and compressors being arranged downstream of the turbine and upstream of the heat exchanger.

4. An installation as claimed in claim 3, wherein the gas of the primary circuit is helium.

5. An installation as claimed in either claim 3 or claim 4, wherein the gas of the secondary circuit comprises an inert gas.

6. An installation for the utilisation of heat generated by a high temperature nuclear reactor, substantially as hereinbefore described with reference to and as illustrated by the accompanying drawings.

New Claims or Amendments to Claims Filed on 1st Oct. 1980
Superseded Claims 1

New or Amended Claims:—

1. A process for the utilisation of heat generated by a high temperature nuclear reactor comprising the steps of circulating gas through a closed primary circuit to a high temperature nuclear reactor at an entry temperature of between 520° and 680°K, heating the gas in the reactor to an exit temperature

of between 1020 and 1220°K, passing the heated gas of the primary circuit through a heat exchanger to transfer heat from the heated gas to compressed gas in a closed secondary circuit, extracting energy from the heated compressed gas under expansion thereof to drive a gas turbine having a pressure ratio between 4 and 12 but above the optimum ratio value, extracting heat from the expanded gas, thereafter cooling the expanded gas in at least two stages, compressing the cooled gas, transferring said extracted heat to the compressed gas, and returning the compressed gas to the heat exchanger for recirculation.

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